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14. ABSTRACT
Laparoscopic Ultrasound probe (Intuitive Surgical, Sunnyvale, CA) was integrated with the daVinci surgical system for use in Robot-Assisted Laparoscopic Prostatectomy (RALP). Automatic robotic-assisted palpation (initially planned for months 18-24) was completed. Additional testing needed before proceeding to clinical use is in progress. The new integrated system has been tested on tissue mimicking phantoms. IRB submission for clinical study is still in preparatory phase. Advances have been made in improving the robustness of our Elastography algorithm and it has also been extended to a 3D version.

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1. INTRODUCTION

Prostate cancer is the second leading cause of cancer death and the most common cancer detected in men in the United States. Radical Prostatectomy (RP) is a surgical procedure with a goal of complete cancer resection. Open radical prostatectomies are associated with loss of blood and lengthy recovery times. Laparoscopic radical prostatectomies (LRP) have a very steep learning curve, lack 3-D visualization and use rigid, stick-like instruments which hinder the dissection. A third technique has recently emerged; laparoscopy using the daVinci Surgical System (Intuitive Surgical, Sunnyvale, CA). The surgical robot introduces many benefits, including three-dimensional visualization, higher magnification, hand tremor elimination and refined dexterity by incorporating wristed instrumentation. Robotic-assisted laparoscopic prostatectomy (RALP) strives to maximize tumor resection and nerve preservation and it has rapidly become the preferred surgical approach. Recent studies have showed RALP is a feasible procedure with a short learning curve, limited blood loss, less post-operative pain, favorable complication rates, and short hospital stay. The lack of tactile feedback is however, one theoretical disadvantage that has been raised with regards to robotic surgery. There is a need for real-time intraoperative guidance in laparoscopic prostatectomies. Hence the objective of this proposal is to develop such a capability. Ultrasound Elastography (USE) is a technology which can be integrated with the robotic probe. Elastography is ideal as a technology as it allows for real-time acquisition of images of the prostate gland and, similar to human palpation, allows for contact based interrogation of the prostate's surface [1]. USE is affordable and minimally invasive and can also be miniaturized and incorporated into robotically assisted prostatectomy. USE using a laparoscopic ultrasound probe (LAPUS) can help the surgeon visualize the anatomy of the prostate gland, identify the contours of the cancerous tumors as well as any extra capsular extension. The contribution of the proposed research project is that it will allow for real-time intraoperative acquisition of images of the prostate gland and the surrounding tissues. We are proposing a safe, simple and robust technique for direct interrogation of the prostate surface aided by a laparoscopic US probe. USE will be a valuable tool in the identification of cancerous lesions and the trajectory of cavernous nerves and thus improve the chances for a cancer-free, nerve-sparing outcome.

2. BODY

This report will address each of the tasks we proposed to accomplish in the Statement of Work during the first year of the award, as outlined below:

Task 2. System Integration and Clinical Evaluation (months 1-12)

2a. Integration, testing, pre-operative plan (months 1-6). We proposed an integration of an existing laparoscopic ultrasound probe (Intuitive Surgical, Sunnyvale, CA) of 7.5 MHz frequency with the daVinci surgical system. We can report the integration has been done successfully in our lab, as shown in the publication submission in Appendix 1 (Billings, S., Nishikant, D., Kang, H. J., Taylor, R., Boctor, E., "System for robot-assisted real-time laparoscopic ultrasound elastography," Pending submission to SPIE Medical Imaging 2012).

Figure 1 shows a block diagram of our complete system for robot-assisted ultrasound elastography. The daVinci S surgical robot is the primary component of our system. The experimental "Read/Write" Research Application Programming Interface (API) provided by Intuitive Surgical Inc. was used to enable robot motion to be controlled from computer in addition to control inputs from the master console. The daVinci robot manipulates a prototype version of a robotically articulated laparoscopic ultrasound probe, also developed by Intuitive Surgical Inc., which was built into the form factor of a standard daVinci tool. The ultrasound probe is driven by a Sonix RP ultrasound system (Ultrasonix Medical Corp., Richmond BC Canada), which provides an Ultrasound Research Interface granting access to pre-beam formed RF data from the ultrasound probe. The RF is read and processed in real time using elastography algorithms developed in our lab. A high-performance external NVIDIA Tesla series GPU, which connects locally to the Sonix RP system, provides sufficient parallel computing power to generate strain images from RF data in real. The elastography images from the GPU are streamed from the Sonix RP system to a network port on the system's central workstation. The workstation also receives a parallel stream of conventional B-mode ultrasound images from the Sonix RP machine directly. The workstation sends both image streams to picture-in-picture overlays shown in the stereo display of the daVinci console (Figure 2). The picture overlays enable the surgeon to observe the ultrasound and elastography image feeds in real-time without releasing control of the robot arms or diverting attention away from the task at hand.

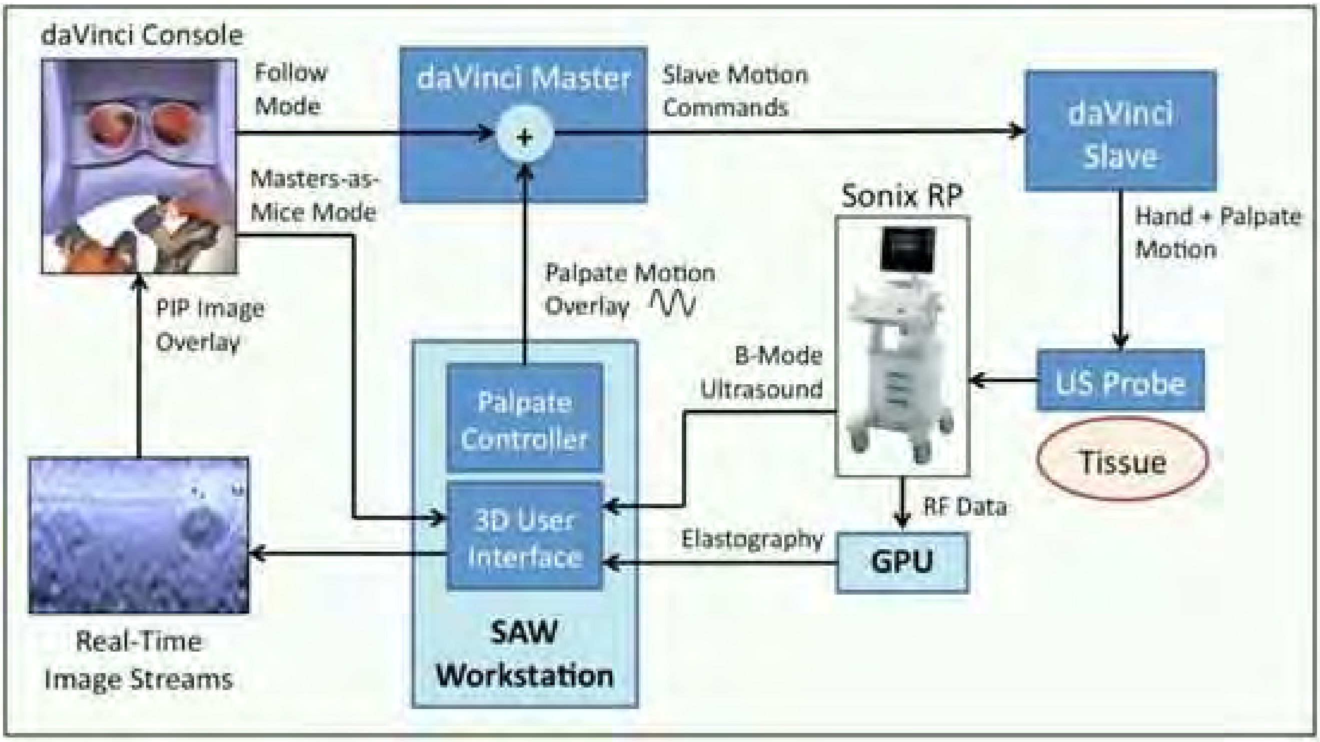

Figure 1. Block diagram of the robot-assisted system for real-time ultrasound elastography

After integration the system was tested on tissue mimicking phantoms. An automatic palpation motion sequence was also implemented. This represents in fact the completion of **task 3c. Automatic robotic-assisted palpation (months 18-24).** The assumption was that automatic pressure application will produce more stable and repeatable images and thus eliminate inter-observer variability in interpretation. In this implementation the tissue is autonomously compressed along the axial direction of the ultrasound probe. The system computer generates a sinusoidal palpation motion that is overlaid onto motion commands from the master manipulators. The surgeon retains control over the position and orientation of the ultrasound probe but the computer provides the tremor-free, precise compression motion necessary for achieving a high quality strain image. Continual palpation of tissue under manual control is a tedious task imposing a large cognitive burden and demand of focus. By relieving this burden through computer assistance, the user is able to focus on more important tasks such interpreting real-time imaging information and conducting surgery.

The results are reported in the same publication attached in Appendix 1 (Billings, S., Nishikant, D., Kang, H. J., Taylor, R., Boctor, E., "System for robot-assisted real-time laparoscopic ultrasound elastography," Pending submission to SPIE Medical Imaging 2012). Figure 2 shows a view of the daVinci console display. The overlay of the elastogram shows a clear differentiation of harder and softer lesions.

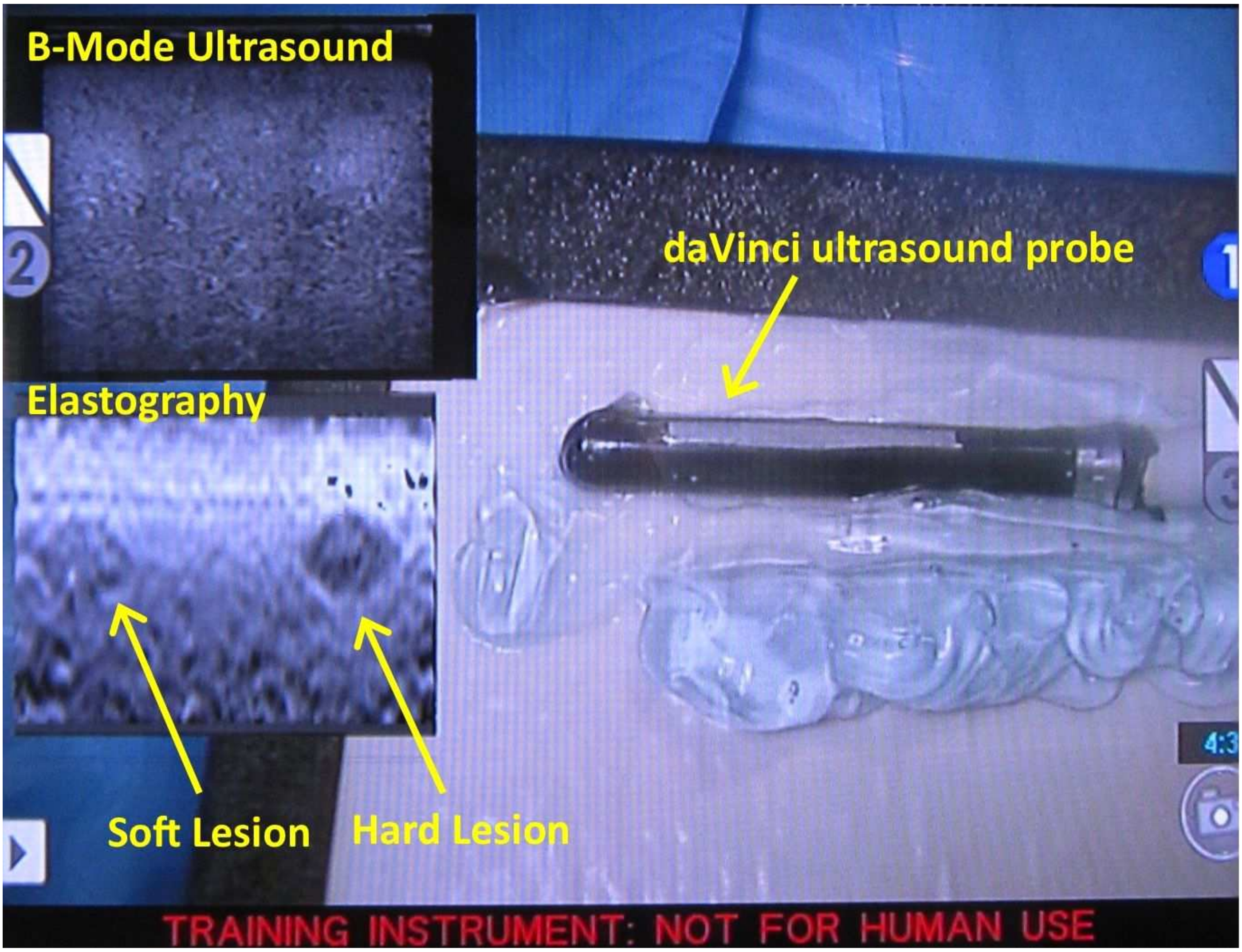

Figure 2. The da Vinci console display showing real-time imaging overlays during a test with an elasticity phantom; the elasticity image differentiates between two lesions of varying stiffness.

Part of task 2a was to work with Dr. Allaf and our clinical team to put together a plan to be carried into the operating room for testing of the laparoscopic ultrasound probe in a clinical setting. This plan would have been done in conjunction with **task 2b: IRB approval (months 1-6)** in which Institutional Review Board approval for a small (N=5-10) clinical study using the LAPUS probe was going to be sought and the subsequent **2c. Clinical evaluation (months 6-12).** Given the successful system integration, the implementation of automatic palpation and the successful testing on tissue mimicking phantoms, our team felt the next step would be to test the system on *ex-vivo* prostate specimens. This comes as an intermediary step and a natural bridge to clinical testing. In the mean time, Intuitive Surgical is also seeking clinical approval for the prototype LAPUS we used in our system integration.

We are working on an Institutional Review Board approval for a medium scale study (N=20-25) on *ex-vivo* excised prostate specimens. The first objective of the study will be to test and evaluate the LAPUS probe. The prostate will be embedded in a gel phantom and it will be scanned using the LAPUS probe. The phantom will be also scanned with a regular ultrasound probe approved for clinical use. A 3D Elastography data set will be collected for each specimen and a database will be created. A box will be build (design in progress) for the specimen phantom with enclosed fiducials which will allow for alignment and comparison of the collected data sets. Additional imaging modalities like MRI can be collected and used for comparison. After imaging, the specimen will undergo macro- and micro- pathological processing. Histopathology represents the gold standard for cancer detection. We will compare our results with the pathological findings.

The second objective of the study will be to prepare for clinical testing of the LAPUS probe. The material surrounding the specimen can be altered so the phantom will mimic the approach of the robotic-assisted laparoscopic prostatectomy. This will help us define image acquisition points and planes. We have to ensure that our probe is able to maneuver and acquire good data suitable for the elastography algorithm. Additionally, our goal is to have no impact on the outcome of the surgical procedure and also not to extend the length of the surgery more than 10-15 minutes.

We have experienced delays in the submission of the IRB due to institutional issues. JHMI (Johns Hopkins Medical Institutions) performs hundreds of prostatectomies every year. We have been working with our busy Pathology department and labs to ensure that our project does not disrupt the day-to-day work flow for pathological processing. The creation and design of our phantom box is one of the results of this collaboration. It will assure that pathologists can process the specimens faster and with higher accuracy, and also (for our study only) the pathologists will be able to create a 3D map of the pathological findings which can be aligned and compared to the Elastography findings. This is not currently the standard procedure at JHMI so an additional effort from our pathology team will be needed, as well as understanding of the special procedure by the JHMI Review Board. The IRB will be submitted in the next month and we anticipate the completion of the study and the evaluation of the data to be done before the end of the second year of the award.

Additional efforts have been made to improve our Elastography algorithm. The robustness of the Dynamic Programming algorithm has been improved and the progress is detailed in a scientific article which has been submitted for publication – Appendix 2 (Fleming, I., Rivaz, H., Boctor, E., Hager, G. “Robust Dynamic Programming Method for Ultrasound Elastography”, Pending submission to SPIE Medical Imaging 2012). This progress was very important as we proceeded in extending our algorithm to 3D, enabling better visualization and understanding of the cancerous lesions, their localization and their extension throughout the prostate. A 3D Elastography has been implemented; we are in the process of evaluating it on simulated ultrasound data and or tissue mimicking phantoms. This effort is a step forward in the completion of **Task 4a-c. Laparoscopic Prostatectomy with Advanced US Imaging Methods (months 21-32)**.

3. KEY RESEARCH ACCOMPLISHMENTS

- Integration of an existing laparoscopic ultrasound probe with the daVinci surgical system.
- Testing of the new integrated system on tissue mimicking phantoms
- Automatic robotic-assisted palpation: design, implementation and testing
- Design of a phantom box to be used in an upcoming study; it will allow for better registration of imaging data sets and also the comparison to the pathology findings
- Improvement of the robustness of our software and the extension of the Elastography algorithm to a 3D version

4. REPORTABLE OUTCOMES

1. Fleming, I., Rivaz, H., Boctor, E., Hager, G. “Robust Dynamic Programming Method for Ultrasound Elastography”, Pending submission to SPIE Medical Imaging 2012.
2. Billings, S., Nishikant, D., Kang, H. J., Taylor, R., Boctor, E., "System for robot-assisted real-time laparoscopic ultrasound elastography," Pending submission to SPIE Medical Imaging 2012

3. CONCLUSION

Laparoscopic Ultrasound probe (Intuitive Surgical, Sunnyvale, CA) was integrated with the daVinci surgical system for use in Robot-Assisted Laparoscopic Prostatectomy (RALP). Automatic robotic-assisted palpation (initially planned for months 18-24) was completed. Additional testing needed before proceeding to clinical use is in progress. The new integrated system has been tested on tissue mimicking phantoms. IRB submission for clinical study is still in preparatory phase. Advances have been made in improving the robustness of our Elastography algorithm and it has also been extended to a 3D version.

4. REFERENCES

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5. APPENDICES

APPENDIX 1: Billings, S., Nishikant, D., Kang, H. J., Taylor, R., Boctor, E., "System for robot-assisted real-time laparoscopic ultrasound elastography," Pending submission to SPIE Medical Imaging 2012

APPENDIX 2: Fleming, I., Rivaz, H., Boctor, E., Hager, G. “Robust Dynamic Programming Method for Ultrasound Elastography”, Pending submission to SPIE Medical Imaging 2012.

System for Robot-Assisted Real-Time Laparoscopic Ultrasound Elastography

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ABSTRACT

Surgical robots provide many advantages for surgery, including minimal invasiveness, precise motion, high dexterity, and crisp stereovision. One limitation of current robotic procedures, compared to open surgery, is the loss of haptic information for such purposes as palpation, which can be very important in minimally invasive tumor resection. Numerous studies have reported the use of real-time ultrasound elastography, in conjunction with conventional B-mode ultrasound, to differentiate malignant from benign lesions. Several groups (including our own) have reported integration of ultrasound with the daVinci robot, and ultrasound elastography is a very promising image guidance method for robot-assisted procedures that will further enable the role of robots in interventions where precise knowledge of sub-surface anatomical features is crucial. In this paper, we present a novel robot-assisted real-time ultrasound elastography system for minimally invasive robot-assisted interventions. Our system combines a daVinci surgical robot with an experimental software interface, a robotically articulated laparoscopic ultrasound probe, and our GPU-based elastography system. Elastography and B-mode ultrasound images are displayed as picture-in-picture overlays in the daVinci console. Our system minimizes dependence on human performance factors by incorporating computer-assisted motion control that automatically generates the tissue palpation required for elastography imaging, while leaving high-level control in the hands of the user. In addition to ensuring consistent strain imaging, the elastography assistance mode avoids the cognitive burden of tedious manual palpation. Preliminary tests of the system with an elasticity phantom demonstrate the ability to differentiate simulated lesions of varied stiffness and clearly delineate lesion boundaries.

DESCRIPTION OF PurPOSE / NEW WORK PRESENTED

Surgical robots provide many advantages for surgery, including minimal invasiveness, precise motion, high dexterity, and crisp stereovision. One limitation of current robotic procedures, compared to open surgery, is the loss of haptic information for such purposes as palpation, which can be very important in minimally invasive tumor resection. Numerous studies have reported the use of real-time ultrasound elastography, in conjunction with conventional B-mode ultrasound, to differentiate malignant from benign lesions in prostate, breast, pancreas, lymph nodes, and thyroid.[1,2,3,4,5] Ultrasound elastography is thus a very promising image guidance method for robot-assisted procedures that will further enable the role of robots in interventions where precise knowledge of hidden anatomical features is crucial. Several groups (including our own) have reported integration of ultrasound with the daVinci robot.[6,7,8] In this paper, we present a novel robot-assisted real-time ultrasound elastography system for minimally invasive robot-assisted interventions.

METHODS

In general, cancerous tissue has higher cell density than surrounding healthy tissue, which leads to elevated tumor stiffness that can be visualized using elastography techniques. As first described by Ophir et al.,[9] the principle of ultrasound elastography is to estimate tissue stiffness from measurement of tissue strain induced by an applied force. This is accomplished by measuring relative tissue displacements between ultrasound image pairs under different states of induced compression. Because ultrasound elastography algorithms assume an axial compression, strain image quality may degrade when non-axial motion or probe rotation occurs during compression. Axial compression is typically on the order of only a millimeter or two, and even small amounts of unwanted motion may affect image quality. Due to the variability in manual compression, image quality for free-hand elastography is highly dependent on practitioner skill and experience.

The quality of elastography imaging as a function of human performance is minimized by our robot-assisted elastography system through computer-integrated motion control for tissue compression, whereby tissue is autonomously compressed along the direction axial to the ultrasound probe. The system computer provides assistive control of robot motion by generating a sinusoidal palpation motion that is overlaid onto motion commands from the master manipulators (Figure 1). By this method, the surgeon retains overall control of the ultrasound probe position and orientation, while the computer controls the finer points of tissue compression. Because the computer has accurate knowledge of the ultrasound probe position and is not subject to motion errors like a human operator, consistent tissue compression in the precise axial direction is ensured.

The elastography assistance mode improves the precision and consistency of tissue compression beyond what can be achieved by manually controlled teleoperation while also reducing the cognitive burden for the user. Continual palpation of tissue under manual control is a tedious task imposing a large cognitive burden and demand of focus. By relieving this burden through computer assistance, the user is able to focus on more important tasks such interpreting real-time imaging information and conducting surgery.

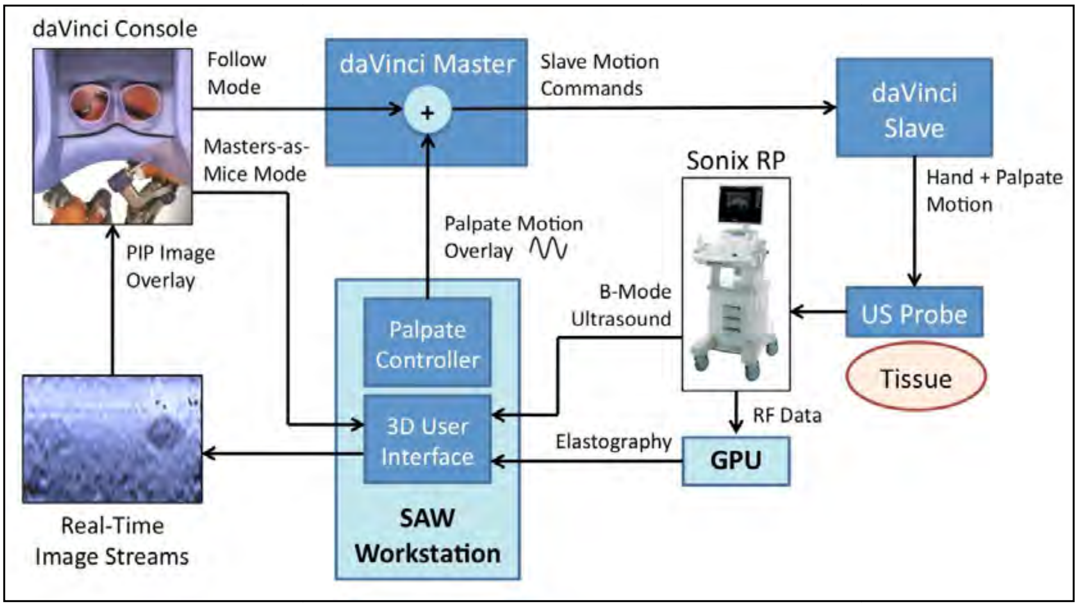

Figure 3. Block diagram of our robot-assisted system for real-time ultrasound elastography.

Figure 1 shows a block diagram of our complete system for robot-assisted ultrasound elastography. At the heart of the system is the daVinci S surgical robot (Intuitive Surgical Inc., Sunnyvale, CA). Computer integrated control of robot motion is facilitated by an experimental "Read/Write" Research Application Programming Interface (API) provided by Intuitive Surgical Inc., which enables robot motion to be controlled from computer in addition to control inputs from the master console, as discussed below. The daVinci robot manipulates a prototype version of a robotically articulated laparoscopic ultrasound probe (Figure 2a), also developed by Intuitive Surgical Inc., which was built into the form factor of a standard daVinci tool. The ultrasound probe has a linear array transducer (Gore, Newark DE) with 128 elements that measures 50mm in length with a probe diameter of approximately 9mm. The ultrasound probe is driven by a Sonix RP ultrasound system (Ultrasonix Medical Corp., Richmond BC Canada), which provides an Ultrasound Research Interface granting access to pre-beam formed RF data from the ultrasound probe. Access to this RF data is critical to reaching optimal performance from elastography algorithms. The RF data is processed by a high-performance external NVIDIA Tesla series GPU, which connects locally to the Sonix RP system. The GPU provides sufficient parallel computing power to generate strain images from RF data in real time using an elastography algorithm based on normalized cross-correlation.[10] The elastography images from the GPU are streamed from the Sonix RP system to a network port on the system's central workstation. The workstation also receives a parallel stream of conventional B-mode ultrasound images from the Sonix RP machine directly. The workstation sends both image streams to picture-in-picture overlays shown in the stereo display of the daVinci console. The picture overlays enable the surgeon to observe the ultrasound and elastography image feeds in real-time without releasing control of the robot arms or diverting attention away from the task at hand.

In collaboration with Intuitive Surgical, the Engineering Research Center for Computer-Integrated Surgical Systems and Technology (CISST ERC) at Johns Hopkins University has developed an open-source software framework for medical robotics and computer assisted surgical systems research, which we call Surgical Assistant Workstation (SAW).[11,12,13,14] This open-source framework is an extension of the CISST software libraries developed at Johns Hopkins to enable rapid application development by providing capabilities including basic mathematics and numerical routines, thread execution management, inter-process communication, construction and control of video pipelines, and many other things.[15,16,17,18] Although the software components providing its basic capabilities are all open-source, SAW is designed to be compatible with proprietary modules through module wrappers using well-defined interface protocols. In particular, we have developed SAW wrappers that provide the ability to interface with the read-only and read-write research interfaces of the daVinci robot. The capabilities of the Read-Only daVinci Research Interface include the ability to query the state of the master and slave robot arms and of user console events.[14] The Read/Write daVinci Research Interface extends these features with the capability to use software to command motions of the master and slave robot arms and to trigger user events. One such feature allows us to superimpose an externally computed motion onto motion inputs from the master manipulators. We use this capability in our system to create computer generated motion overlays for tissue palpation. Another function of SAW allows us to use a master arm controller effectively as a 3D mouse. We call this masters-as-mice mode. We use this mode in our system to build an interactive environment for the daVinci operator to control and interact with video overlays.

The SAW software package is implemented on the central workstation of our system, which centralizes processing for user interaction with image overlays, acquisition of real-time image streams, and implementation of the control loop generating assistive motion for tissue palpation. A command terminal on the central workstation allows the user to set the amplitude and frequency of tissue palpation. These settings may be updated in real-time. The terminal also allows palpation to be activated/deactivated at will. The user interacts with the image overlays from the daVinci console using the SAW masters-as-mice mode, which, for the daVinci system, is activated by engaging the clutch foot pedal followed by a double-pinch of both master manipulators in unison. The masters-as-mice mode activates an interactive menu environment in which the daVinci master controllers manipulate virtual cursors in the daVinci console's stereo display (Figure 4a). Menu selections are made by moving a cursor to a menu icon and pinching the corresponding master controller. The elastography and B-mode ultrasound image overlays are activated by selecting the appropriate menu icon with a virtual cursor (pinching master controller selects). The image overlays are resized and repositioned in the daVinci display by dragging them with a cursor. Releasing the clutch pedal returns the master manipulators to control of the slave arms and maintains the image overlays in the user's field of view.

Results

Preliminary tests of the system have been conducted with a CIRS Model 049 Elasticity QA Phantom, which has simulated lesions of different calibrated stiffness. Figure 4b presents a snap-shot of the daVinci display taken during phantom testing with image overlays displaying the real-time imaging results. The elastography image in this figure shows clear difference in contrast between a soft and hard lesion, with the hard lesion appearing darker in the image. This distinction cannot be made from the B-mode ultrasound image in this figure. The elastography image also establishes clear delineation of lesion boundaries, which would not be discernible from B-mode ultrasound in the case of isoechoic lesions. These images were recorded with tissue palpation set to 1mm amplitude and 1Hz frequency.

CONCLUSION

We have successfully implemented a robot-assisted system for minimally invasive, real-time ultrasound elastography. Our system provides an improvement over manual elastography techniques by unifying motion commands from a user with the precision and accuracy of computer-assisted motion control to ensure consistent and precise tissue strain. Our approach effectively reduces the cognitive load of the human operator while maintaining a user's control of the procedure. Preliminary tests using an elasticity phantom demonstrate the system's capability to generate strain images in real-time that can be used to delineate simulated lesion boundaries and differentiate lesions of varying stiffness.

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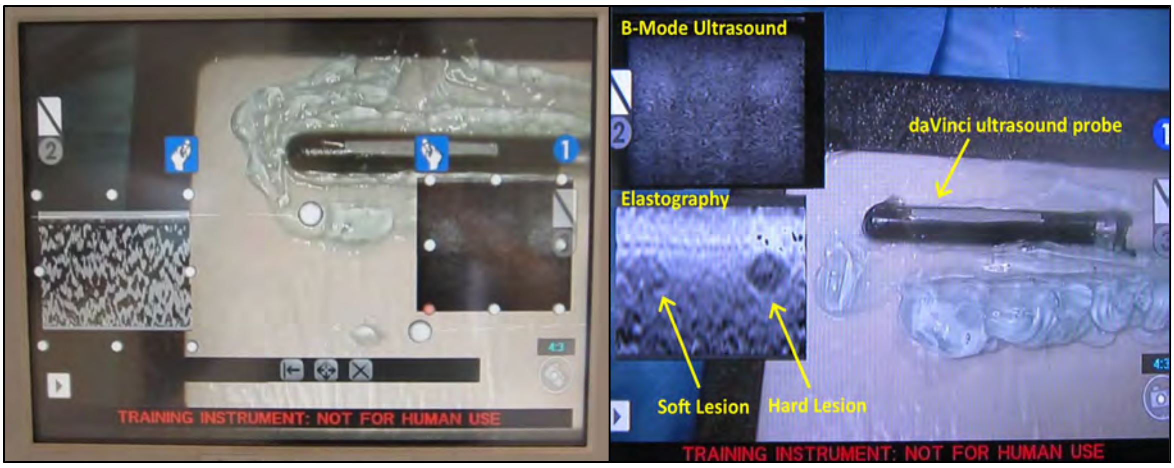

(a) (b)

Figure 4. a) Interactive menu environment for displaying image overlays in the daVinci console display, showing an active menu with two virtual mice corresponding to the left and right master manipulators and two picture-in-picture image overlays (picture taken of a patient side monitor). b) View of the daVinci console display during a test with an elasticity phantom; the elastography image overlay differentiates lesions of different stiffness.

THIS WORK HAS NOT BEEN SUBMITTED FOR PUBLICATION OR PRESENTATION ELSEWHERE.

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Robust Dynamic Programming Method for Ultrasound Elastography

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Abstract. Ultrasound elastography is an imaging technology which can detect differences in tissue stiffness based on tissue deformation. Initially introduced more than two decades ago, ultrasound elastography is recently establishing itself as a valuable tool for diagnostic and monitoring. For clinical successful use in cancer diagnosis and monitoring the method should be robust to sources of decorrelation between ultrasound images. A regularized Dynamic Programming (DP) approach was used for displacement estimation in compressed tissue. In the Analytic Minimization (AM) extension of DP, integer displacements are calculated just for one RF-line, and are then propagated lateraly throughout the entire image. This makes the *seed* RF-line very important; faulty *seed* lines could propagate erroneous displacement values throughout the image resulting in the appearance of false lesions. In this paper we analyze the robustness of this method in free-hand palpation of laboratory tissue phantoms. We are proposing an update to the algorithm which includes detection of faulty DP RF-lines in decorrelated areas and solutions for improving the robustness of the DP approach, while maintaining real-time computation of strain images. Axial integer displacement is obtained on each RF-line individually using DP optimization. The values are then compared among adjacent lines and several metrics are considered which could detect faulty RF-lines. We are considering the use of filters to enforce smoothness and similarity among neighboring RF-lines. The method is tested and the results are compared between computer simulated and laboratory tissue phantoms.

1 Background and Rationale

Ultrasound Elastography is an imaging technology which can detect differences in tissue stiffness based on tissue deformation. Our work in this paper focuses on real-time quasi-static elastography. The tissue is compressed and relaxed in a continuous free-hand motion and ultrasound images are simultaneously acquired. This method is easy to use and also cheap as it requires no extra hardware. This makes it particularly appealing for medical imaging applications; diagnosis or monitoring could be done at the patient's bed side. There are two hurdles which once resolved would ensure success for clinical use: real-time computation of strain images and dealing with the potential for global and local decorrelation between pre- and post-compression ultrasound images. Various sources of decorrelation are affecting the computation of strain images in *in-vivo* data, such as incoherent fluid (blood) motion, out-of-plane motion of structures within one image due to transducer or respiratory motion, subsample speckle motion, and a high degree of compression.

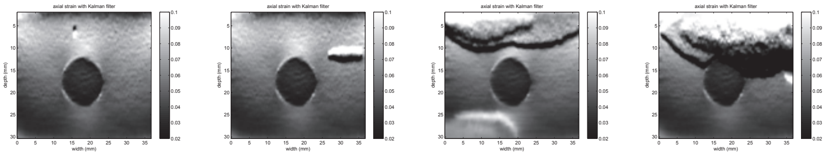
Rivaz et al (2008) initially proposed optimizing a recursive regularized cost function using Dynamic Programming (DP). The method resulted in integer values for axial displacement and subsample displacement could also be achieved but at a high computational cost. Rivaz et al (2011) refined the method further using a 1D and 2D Analitic Minimization (AM) of the cost function. It takes the integer displacement of a single radio frequency (RF)-line from DP and produces the subsample axial and lateral displacement fields for the entire image.

In this work we analyze the robustness of the AM2D method. Since this method is based on computing integer displacements using DP on only one RF-line, it is crucial that we choose a starting line with little or no decorrelation between the two images. Here we present a method for identifying faulty DP lines and reducing their potential to generate artifact lesions.

2 2D AM subpixel displacement estimation

Here we briefly review the 2D AM method in which 2D integer displacements are first obtained using DP on a single RF-line and are then used to produce 2D subsample displacements for the entire image.

1. Calculate integer axial and lateral displacements of one *seed* RF-line using DP (Rivaz et al, 2008). Calculate an initial subsample estimate using linear interpolation of the integer displacements.
   Let I_1 and I_2 be two ultrasound images acquired before and after deformation. Let m be the number of RF-lines. Each signal is sampled at $i = 1,\ 2 \cdots m$. A regularized cost function is generated combining the prior of displacement continuity (regularization term) and an amplitude similarity term. The displacement continuity term for line j can be written as:
   $$R_j(a_i, l_i, a_{i-1}, l_{i-1}) = \alpha_a (a_i - a_{i-1})^2 + \alpha_l (l_i - l_{i-1})^2 \tag{1}$$
   where α_a and α_l are axial and lateral regularization weights respectively. The regularized cost function at the ith sample of the jth A-line becomes:
   $$\begin{gathered} C_j(a_i, l_i, i) = [I_1(i,j) - I_2(i + a_i, j + l_i)]^2 \\ + \min_{d_a, d_l} \left\{ \frac{C_j(d_a, d_l, i-1) + C_{j-1}(d_a, d_l, i)}{2} + w R_j(a_i, l_i, d_a, d_l) \right\} \end{gathered} \tag{2}$$
   where w is a regularization weight for smoothness; d_a and d_l are temporary axial and lateral displacements that are varied in order to minimize eqn. (2).
2. Calculate subsample axial and lateral displacements for the *seed* RF-line using 2D AM (below). They will be added to the initial integer estimates.
3. Propagate the solution of the *seed* RF-line to the left and right. using the displacement of the previous line as initial estimate.
   The aim is to calculate Δa_i and Δl_i such that the duple $(a_i + \Delta a_i, l_i + \Delta l_i)$ gives the axial and lateral displacements at the sample i. The regularized cost function becomes: where the index j was dropped for the j^{th} RF-line and $l_{i,j-1}$ is the lateral displacement of the previous RF-line (except for the



(a) (b) (c) (d)

Fig. 1. Strain images from breast phantom freehand palpation using DP AM2D method. Note most artifacts occur in the upper part of the phantom. Only 1 (one) faulty line (line #476) produced an artifact which obscured the actual lesion

seed line where $l_{i,j-1} = l_i$. α, β_a and $\beta_l^{'}$ are regularization terms which ensure continuity in displacements with respect to the top (axial α), and the top and left/right (lateral β_a and $\beta_l^{'}$). If the displacement of the previous line is not accurate, it will affect the displacement of

$$\begin{aligned} &C_j(\Delta a_1, ..., \Delta a_m, \Delta l_1, ..., \Delta l_m) \\ &= \sum_m^{i=1} \{[I_1(i,j) - I_2(i + a_i + \Delta a_i, j + l_i + \Delta l_i)]^2 \\ &+\alpha \left(a_i + \Delta a_i - a_{i-1} - \Delta a_{i-1}\right)^2 \\ &+\beta_a \left(l_i + \Delta l_i - l_{i-1} - \Delta l_{i-1}\right)^2 \\ &+\beta_l^{'} \left(l_i + \Delta l_i - l_{i,j-1}\right)^2\} \end{aligned} \tag{3}$$

the next line through the last term in the right-hand side of (3).

3 Experimental Design and Results

For experimental evaluation we palpated a breast elastography phantom with a 10mm ϕ lesion and three times stiffer than the background. RF data was acquired with a 7.27MHz linear array at a sampling rate of 40MHz. We evaluated the percentage of *seed* RF-lines with wrong DP displacement estimations. The DP displacement computation uses a smoothness regularization parameter w (2) which should prevent regions with high local decorrelation from introducing errors in displacement estimation, but if chosen too large would result in over-smoothing. We used 3 (three) values for w: 0.15, 0.3 and 0.6. The percentage of faulty *seed* lines was 38.8, 30.43, and 74.4. Here we report on the $w = 0.3$ case.

Many of the artifacts created by the erroneous displacement estimation were very small (fig. 1 a) and localized at the top of the image. Some artifacts were large, sometimes propagating through a big part of the image and, in only one case, the resulting artifact lesion obscured the real lesion (fig. 1 d). The distribution of the faulty lines across the image is plotted in (fig. 2). The lines appear to align with peaks and nadirs in mean displacement; this could be a potential indicator for faulty lines.

The change in mean displacement for each RF-line could be a metric which would be able to separate faulty RF-lines. Sometimes a group of adjacent lines

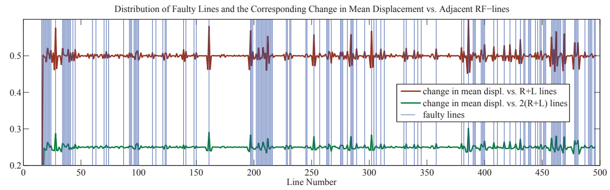
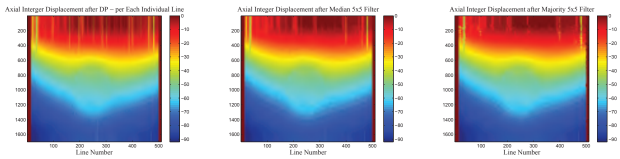


Fig. 2. The distribution of faulty lines (blue) and the corresponding change in mean pixel displacement. The change is calculated vs. 2 adjacent right and left RF-lines (red) and also vs. 4 adjacent lines(green))



(a) (b) (c)

Fig. 3. Initial axial integer displacement estimation (a), after median 5x5 filter (b) and after majority vote 5x5 filter (c)

can all be faulty, so we computed this metric in 2 ways:

$$\begin{aligned}
\Delta d_j^1 &= \textstyle\sum_m^{i=1}\{a_{i,j}\} \div \left[\sum_m^{i=1}\{a_{i,j-1}\} + \sum_m^{i=1}\{a_{i,j+1}\}\right] \\
\Delta d_j^2 &= \textstyle\sum_m^{i=1}\{a_{i,j}\} \div \left[\sum_m^{i=1}\{a_{i,j-2}\} + \sum_m^{i=1}\{a_{i,j-1}\} + \sum_m^{i=1}\{a_{i,j+1}\} + \sum_m^{i=1}\{a_{i,j+2}\}\right]
\end{aligned} \tag{4}$$

where $a_{i,j}$ is the integer axial displacement of pixel i on the RF-line j. The expected value of Δd_j^1 should be very close to 0.5, and 0.25 for Δd_j^2 .

There are 202 RF-lines with $0.495 \leq \Delta d_j^1 \leq 0.505$ compared to 145 faulty RF-lines. Only 71.71% of faulty RF-lines (104) are picked out as true positives. For detection of all faulty lines one would need to adjust the threshold to 0.5002 and 0.4998, which also leads to many false positives: 452 RF-lines out of the total of 477 (94.75%) would be deemed faulty. Similarly with Δd_j^2: 96.2% of lines would be found faulty in order to select all the true faulty RF-lines. 78.62% of lines are selected as true positives when 248 lines (52%) of all lines are found positive ($0.248 \leq \Delta d_j^2 \leq 0.252$). The large number of false positives makes this method alone not a very good predictor of faulty lines. It is however clear faulty RF-lines could be adjusted after DP displacement computation in order to obtain a smaller change in mean displacement. We implemented and tested median filters as well as a majority vote approach. Results are summarized in fig. 3. Multiple filter passes will result in further decreases in faulty *seed* lines.
Note: This work has not been submitted for publication to any other venue.